Laser acceleration of electrons at Femilab/Nicadd photoinjector

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- FNPL energy upgrade
- Laser acceleration
- Open iris-loaded structure concept
- Phase matching issues
- Degrading effects
- Performance studies for the FNPL beam parameters

The FNPL experiment (NOW)

- **Since mid 90's:** FNAL operates a high brightness photo-injector (A0 now FNPL)

- Copy of FNPL was installed at TTF-1 (DESY) and supported SASE-FEL operation (100 nm)

Main beam parameters:

E= 16 MeV

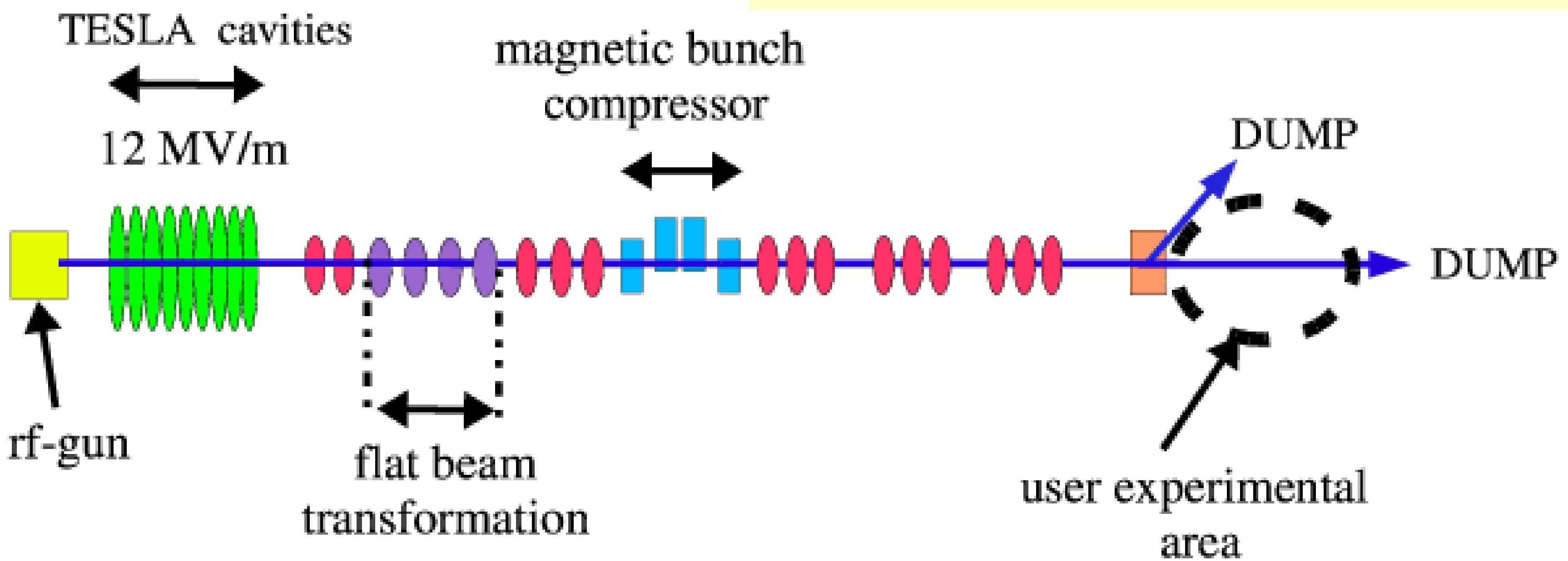
Q= 0 to 15 nC,

ε_T =3.7 mm-mrad (1 nC)

δp/p=0.25 % (1 nC)

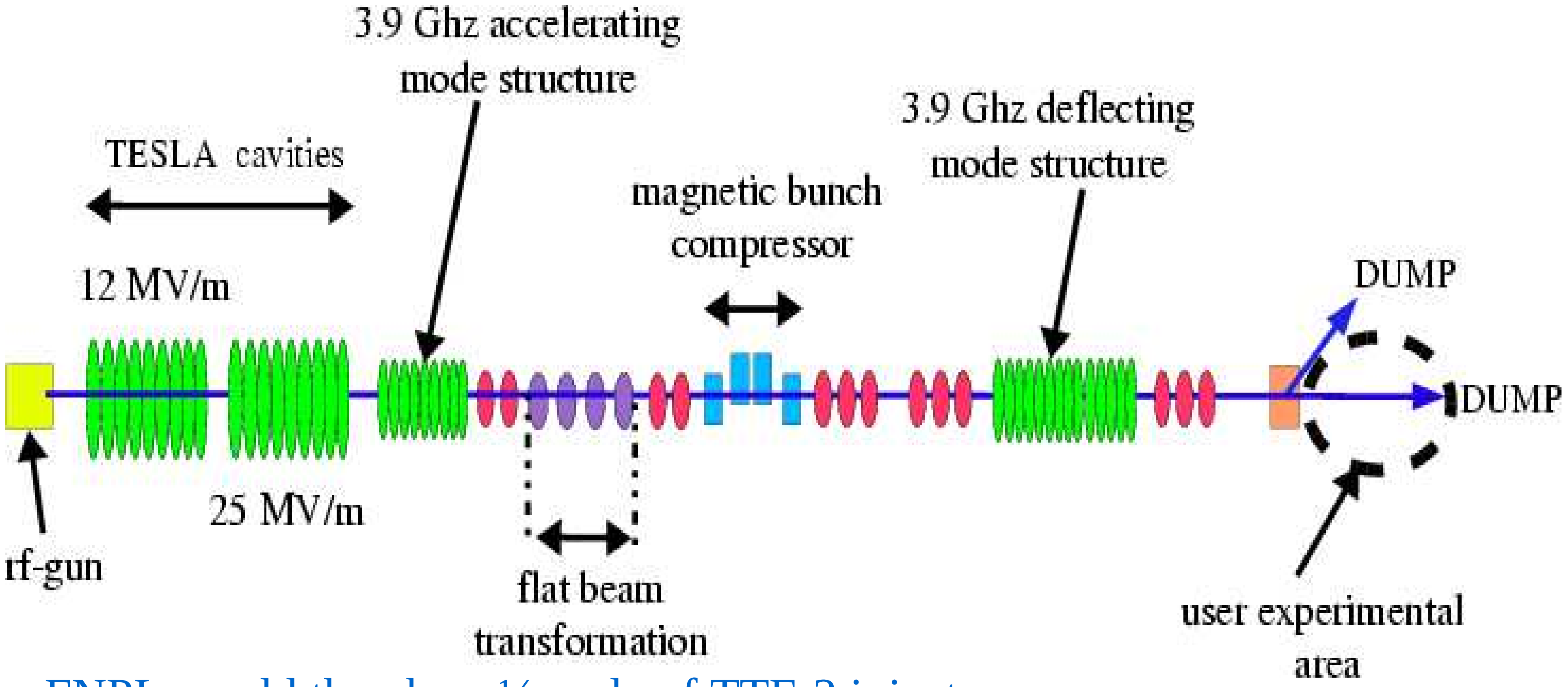
I_{peak} = 75-330 A (BC off)

I_{peak} = 200-1700 A (BC on)



FNPL energy upgrade (next year)

- DESY has offered to give a TESLA cavity (Grad.>25 MV/m)
- Proposed upgrade also incorporate the "CKM deflector" (3.9 GHz deflecting cavity) and eventually a 3.9 Ghz accelerating mode cavity being developed at FNAL in the context of TTF-FEL 2 accelerator



FNPL would then be a ¼ scale of TTF-2 injector

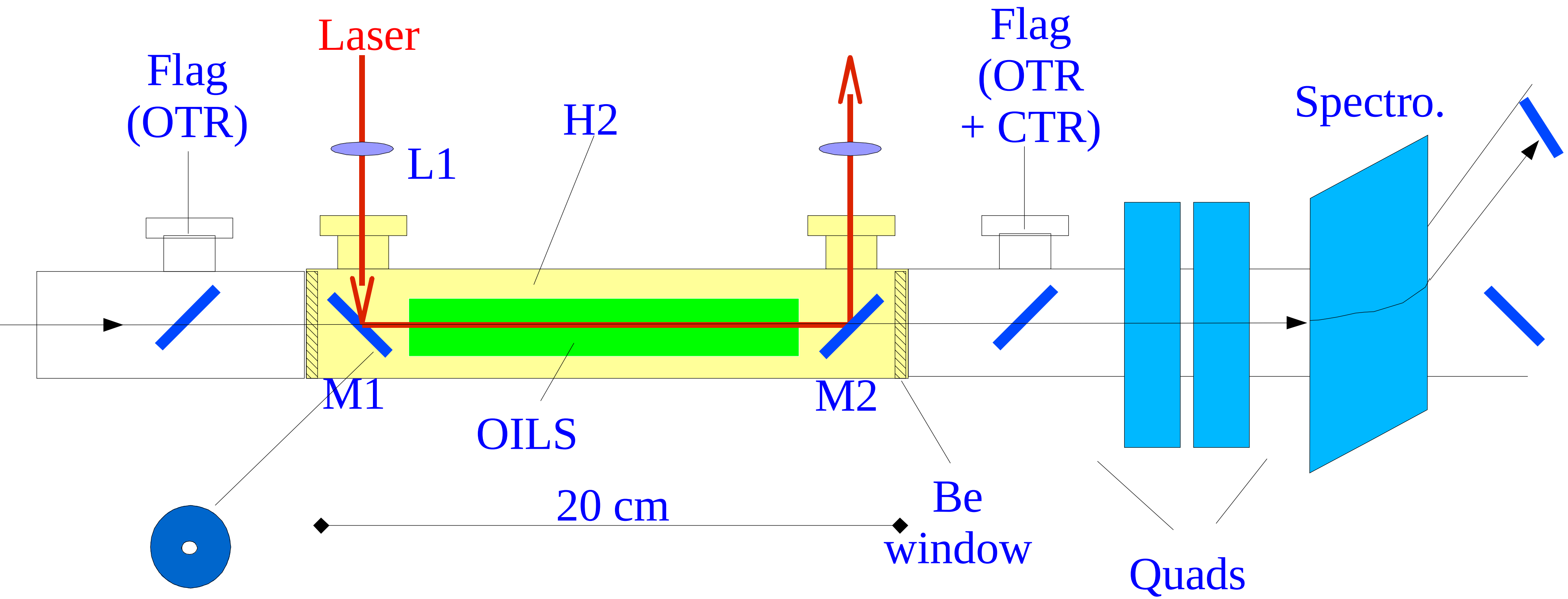
FNPL energy upgrade (next year)

- Investigated/optimized low-charge operation of FNPL (Q=100 pC)

Parameter	**Value**	**Unit**
E-field on cathode	35	MV/m
laser launch phase	40 (wrt 0-Xing)	rf-deg
cavity 1 aver. gradient	12.5	MV/m
cavity 1 phase	0 (on-crest)	rf-deg
cavity 2 aver. gradient	25.0	MV/m
cavity 2 phase	-10 off-crest	rf-deg
rms laser pulse	5	ps
rms laser spot size	0.5	mm
charge	100	pC
total energy	43	MeV
transverse emittance	0.7	mm-mrad
bunch length	0.5 (1.7)	mm (ps)
momentum spread	5.5	keV

Laser acceleration of electrons

- Incoming electron beam E=40-50 MeV is co-propagated with the laser in a OILS structure immersed in a pressurized H2 tank

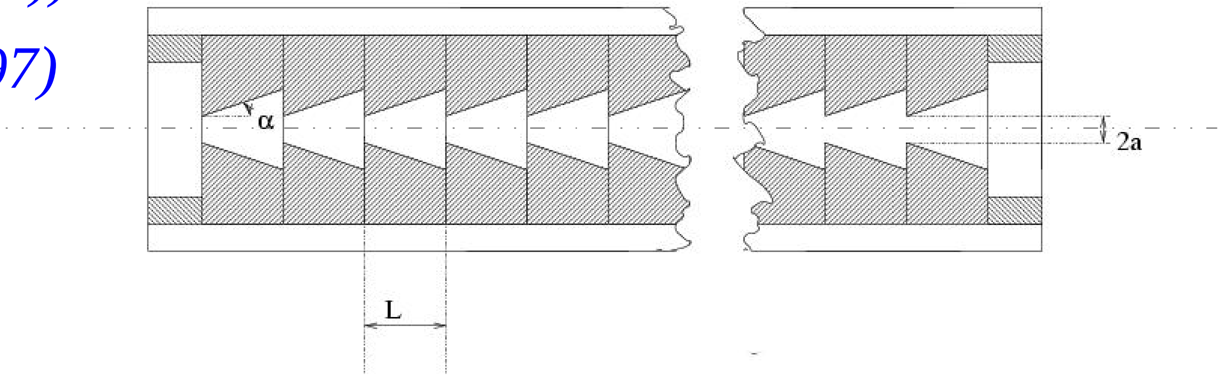


- Diagnostic to measure beam size, coherent transition radiation, + spectrometer for momentum/momentum spread measurement

The Open Iris-loaded structure

R. Pantell (NIM A 393 1-5 (1997))

M. Xie (LBNL-40558 and PAC97)



- The fields associated to TM_{01} eigenmode are given by:

$$E_z(r,z,t)=\widehat{E}\,J_0(k_r r)\exp(i(k_z z-\omega t))$$

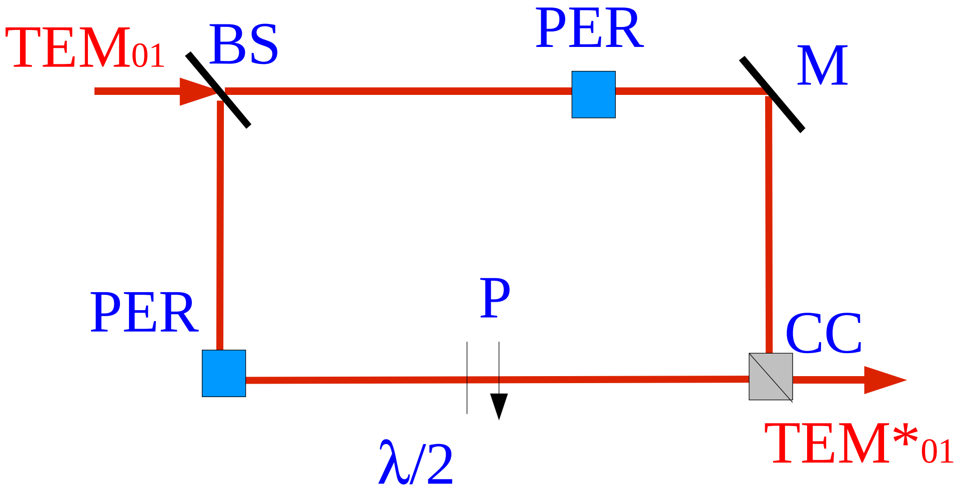
$$E_r(r,z,t)=Z_{TM}H_\phi=-i\frac{k_z}{k}\widehat{E}\,J_1(k_r r)\exp(i(k_z z-\omega t))$$

- The phase velocity of the wave is:

$$v_\phi=\frac{\omega}{\Re(k_z)}\approx\frac{c}{n}[1+\frac{1}{2}(\frac{p_{10}\lambda}{2\pi a})]$$

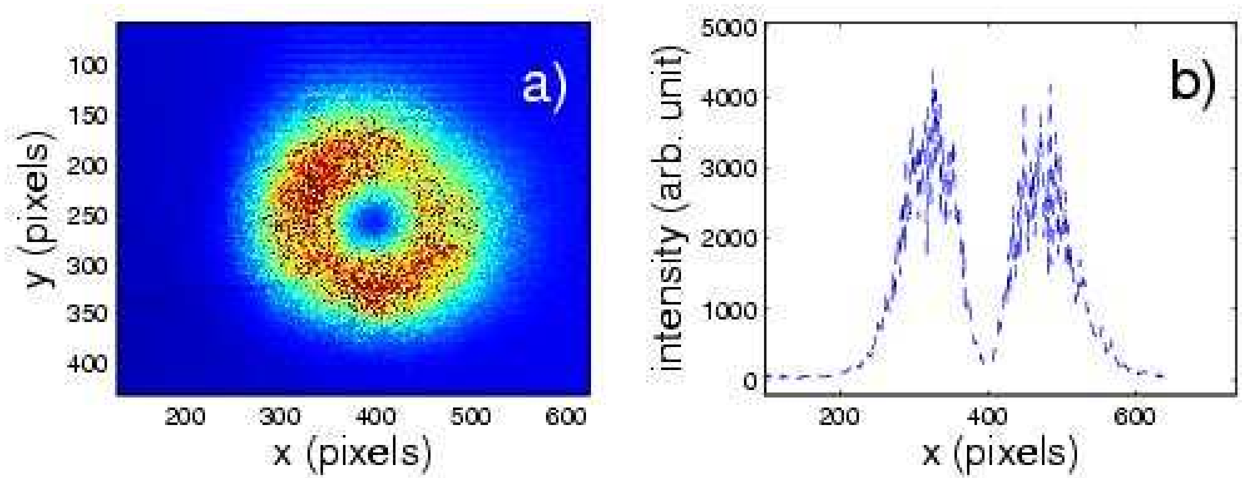
Wherein λ: wavelength, $J_1(p_{10})=0$, *n* refractive index, *c* velocity of light

Generation of "donuts" mode



-The TEM01 mode is generated by a regen. Nd:glass laser seeded by the oscillator of the photocathode drive laser

- The TEM*01 is then obtained using a Mach-Zender interferometer



R. Tikhoplav et al.(EPAC2002 984-985 (2002))

Laser and structure parameters

Parameter	Value	Unit
Structure parameters		
length	10 (25)	cm
iris diameter	2a=1	mm
number of stacked element	50 (125)	-
element thickness	L=2	mm
wavelength	1054	nm
energy per pulse	0.020 (2)	J
pulse length	~2	ps

Phase matching issues

-At injection to enable interaction between the wave and electrons we must match the refractive index to:

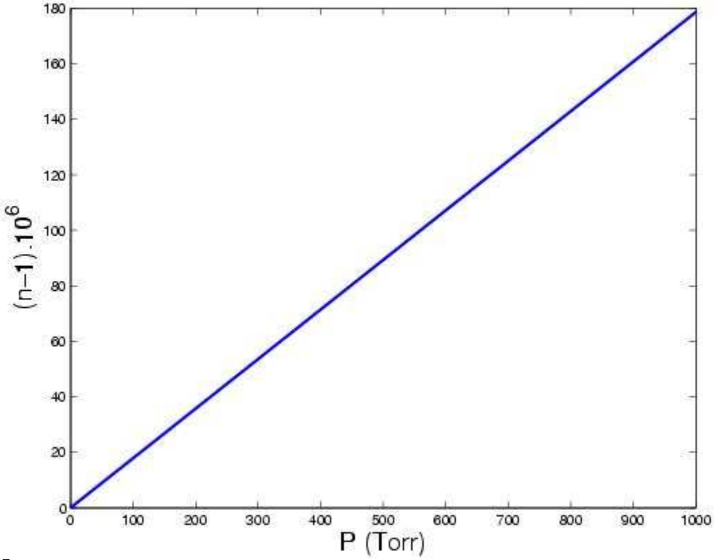
$$n-1=\frac{1}{2}\left[\left(\frac{p_{01}\lambda}{2\pi a}\right)^{2}+\frac{1}{\gamma_{inj}^{2}}\right]$$

- This can be done by introducing a gas at the proper pressure. Hydrogen gas is the best choice in our case (it has been used in GFEL porject with beam parameter similar to ours). The refractive index is given by:

[Torr]

$$n-1=10^{-6}\frac{P}{760}\frac{273.15}{T}\left(21.113+\frac{12723.2}{111-\lambda^{2}}\right)$$

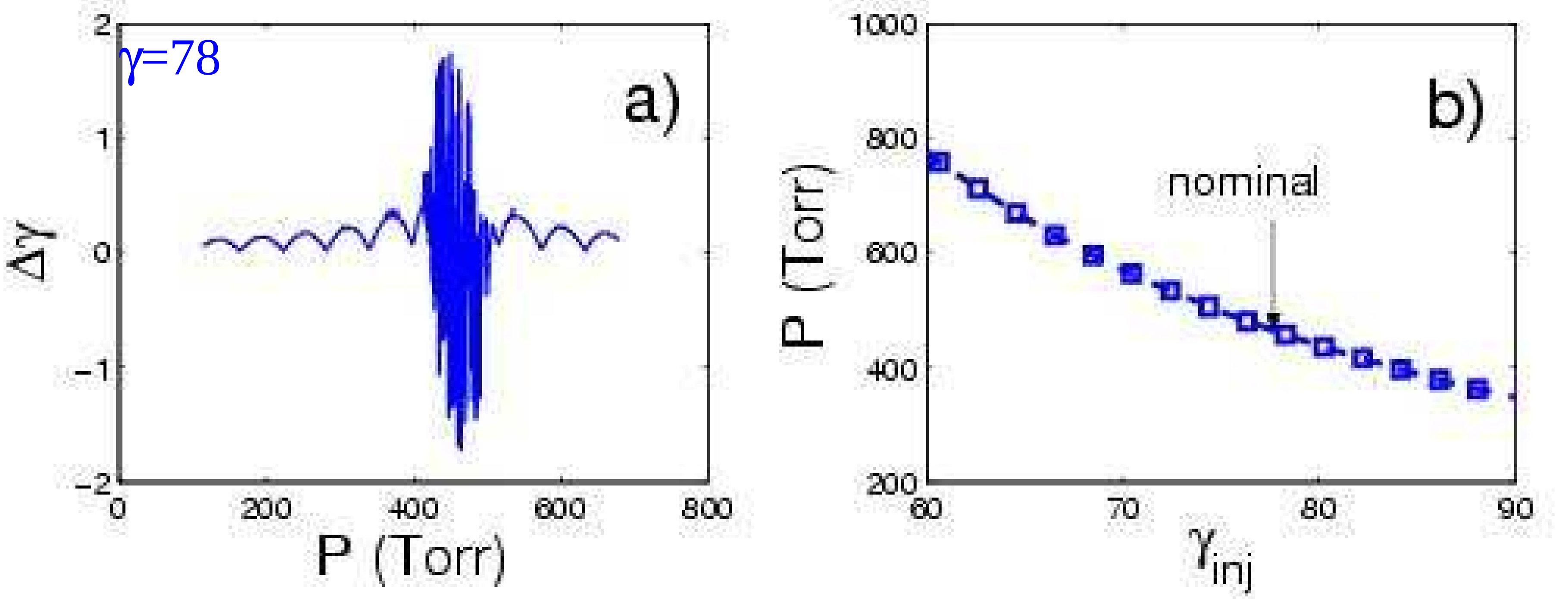
[K] [micron]



Phase matching issues

-For a nominal injection energy of 40 MeV (γ=78) we need *n*-1=0.000083 which corresponds to 450 Torr of H2 gas at 273.15 K

- higher injection energy will require lower pressure



Degrading effects

-**Emittance growth** due to **beam-scattering** in entrance/exit windows and gaz volume:

$$\Delta \gamma \epsilon_{x,y} \approx \left[\sum_i \frac{2}{3} \left(\frac{28}{\gamma}\right)^2 \left(\frac{L_i^2}{X_{0,i}}\right)\right]^{1/2}$$

$X_{0,i}$: radiation length of considered element and L_i electron path length in the element. Most of the emittance growth contribution come from beam-scattering in the H2 gas and would results in a beam blow up by a factor ~2-3 at the end of gas cell (still tolerable). However interpolation of experimental results from Ref. [*Fisher et al. NIM A250 337-341 (1986)*] indicate our simple estimate seems pessimistic.

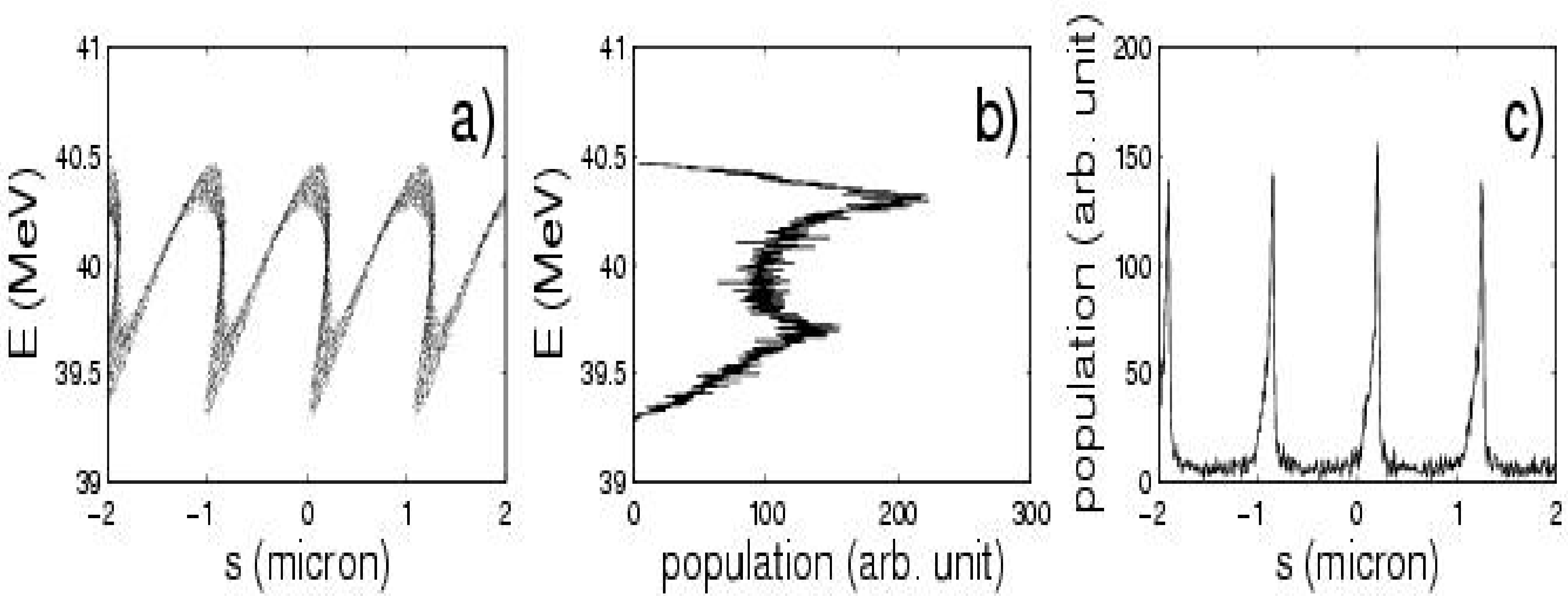
-**Momentum spread dilution** due to **wake field**: at 100 pC and 0.5 mm our peak current is only ~25 A so the corresponding momentum spread is small, in anycase "difference measurements" can be done

Microbunching

Given the momentum spread correlation, after a length L obeying:

$$\frac{1}{\gamma}\frac{d\,\Delta\gamma}{d\,\gamma} \approx \frac{-\gamma^{2}}{L}$$

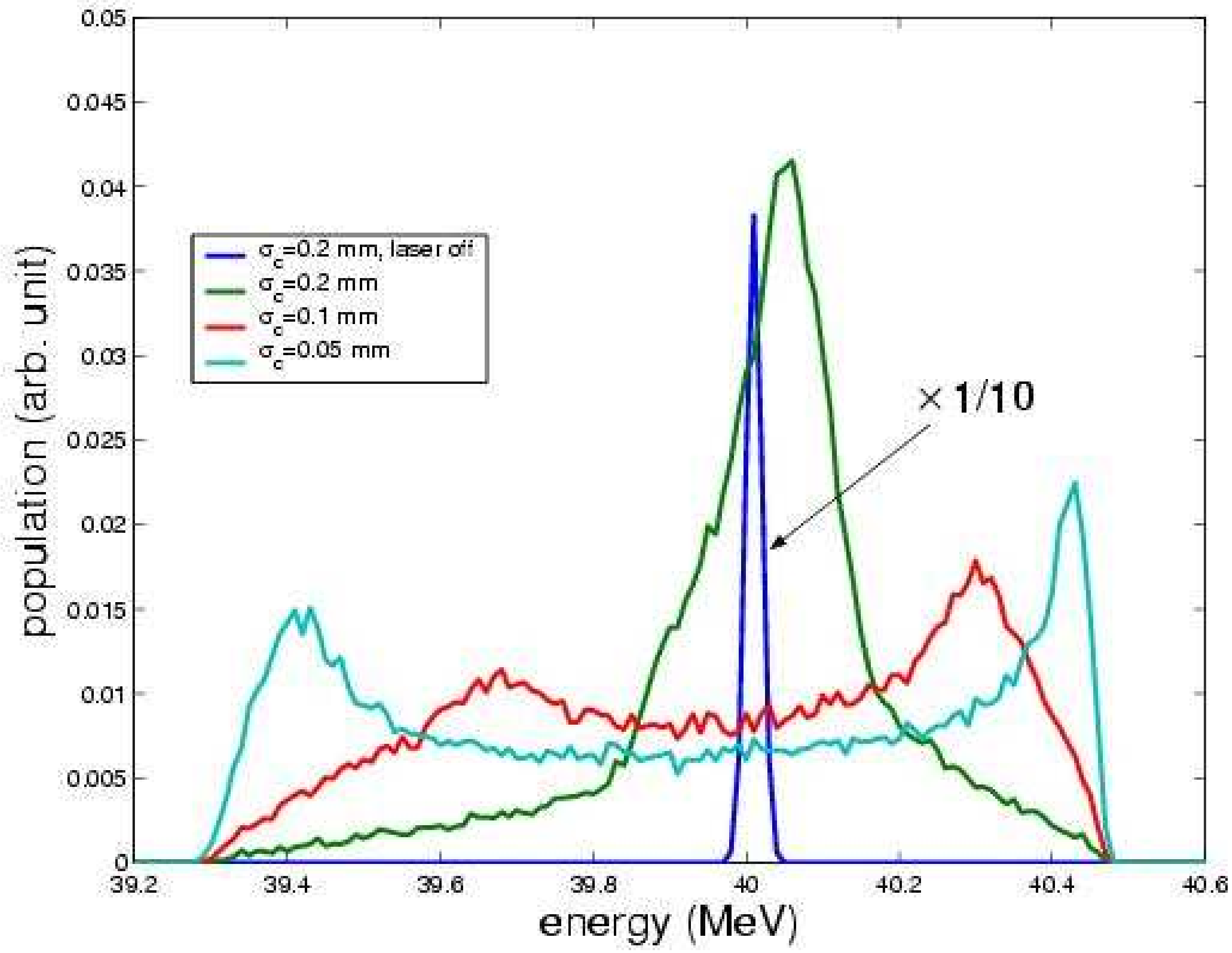
the phase space will locally be compressed, this would results in micro-bunching (density modulation of the bunch)



Longitudinal phase space and projections10 cm downstream of the OILS structure

Energy spectrum

Evolution of the energy spectrum for various beam size propagating in the laser field



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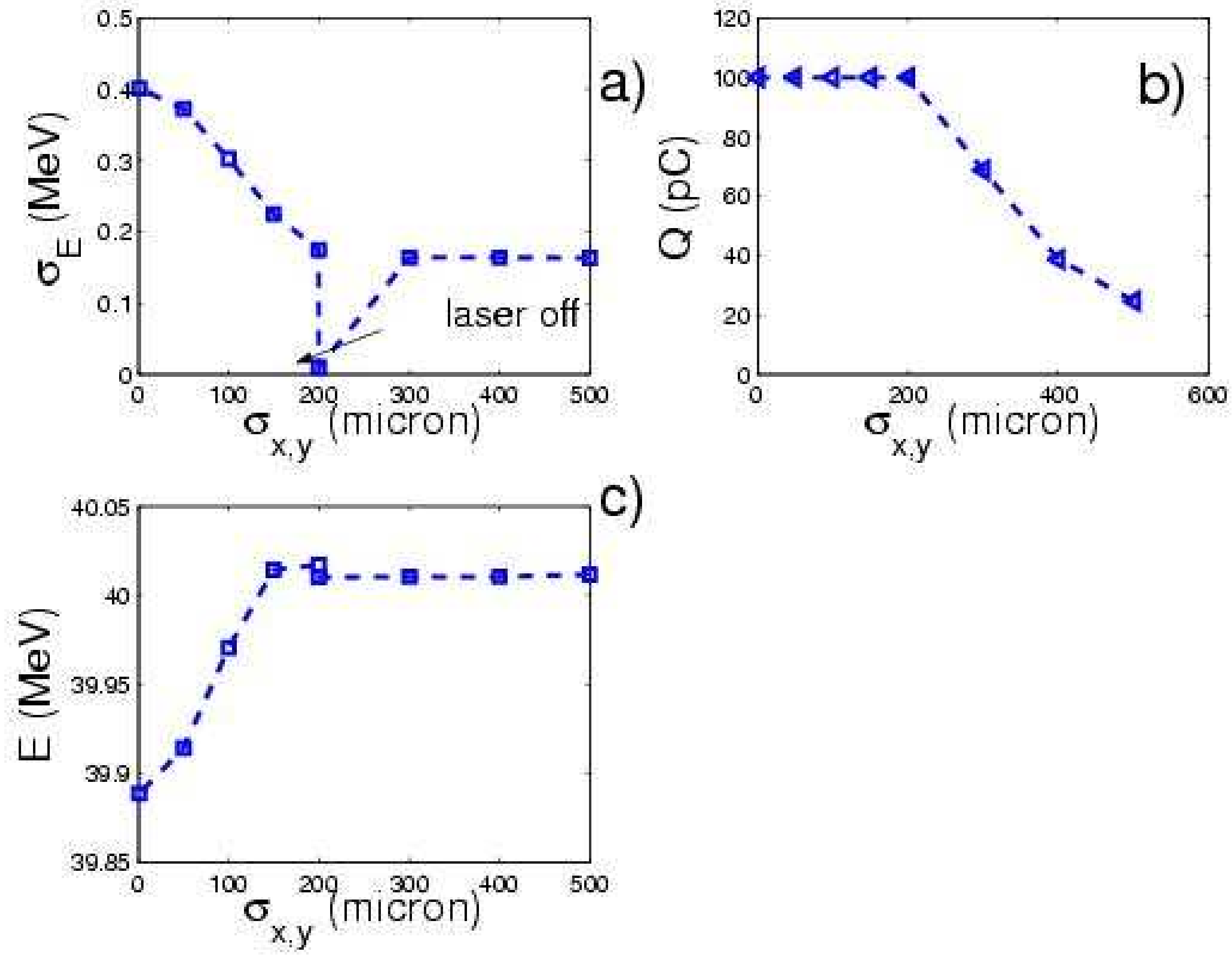
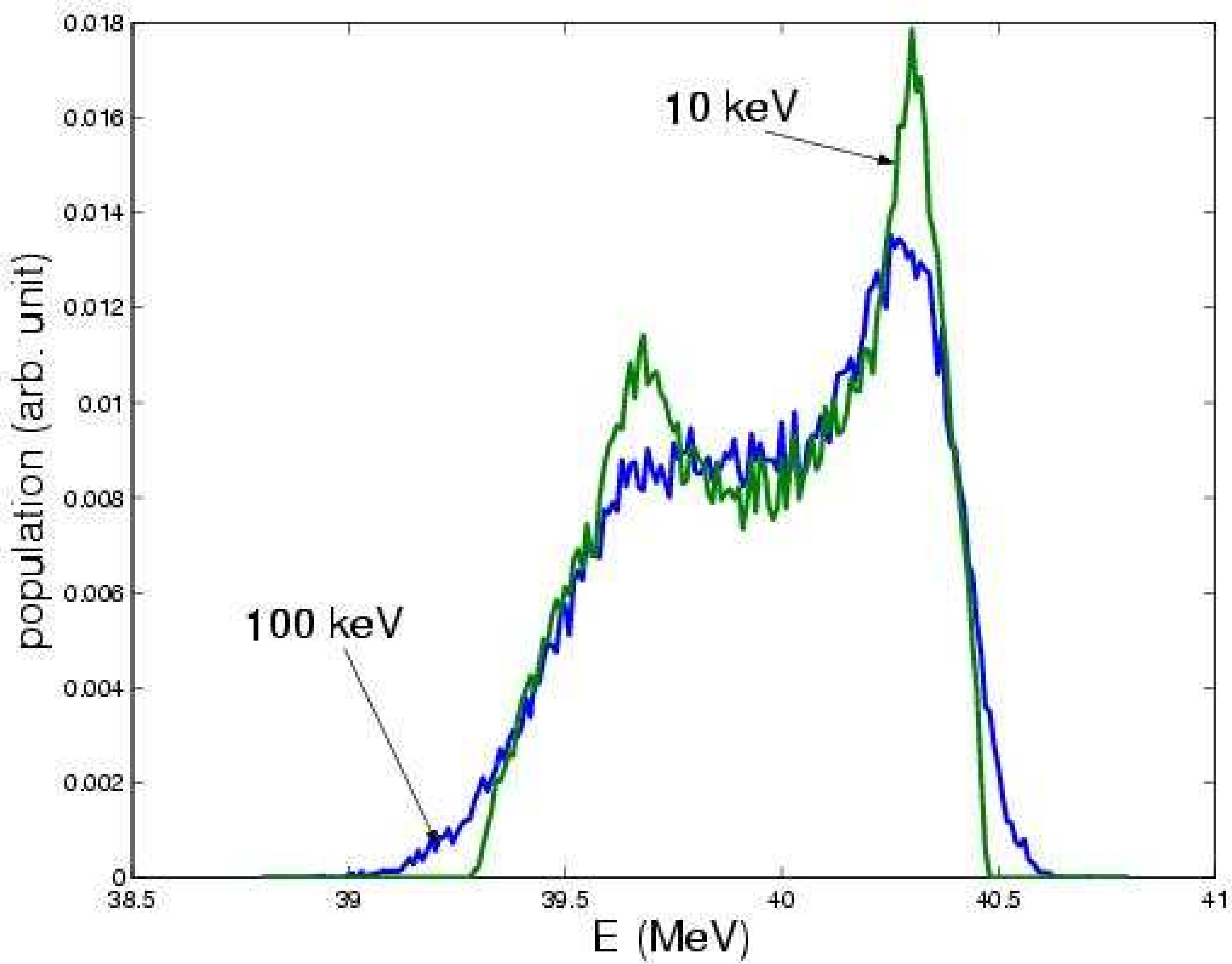


Energy spectrum

Evolution of the energy spectrum for various e- beam momentum spread



Conclusion

-We have revisited an early proposal to investigate laser acceleration at low energy (40-50 MeV) at FNPL [*R. Tikhoplav Research Brief for PhD qualification, U. of Rochester (2002)*]

- Simulation of the experiment based on realistic performance expected after the energy upgrade of FNPL have been performed based on a simple model of the laser/electron interaction included in the ASTRA tracking program

- our primary conclusion are:
  1/ the experiment should provide a clear signature of laser/electron interaction via micro-bunching and energy modulation observation
  2/ varying the gas pressure will provide a knowb to study the laser/e- interaction for various injection energies

- a refinement of our simulation model is on-going to include beam-scattering processes in the gas and windows + laser out of the OILS